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The research of a new type of sensor dynamic compensation technology

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Abstract The applications of FIR filter on dynamic compensation of sensors are dealt with in this paper. The principle and algorithms are introduced. The main advantage of the design is its flexibility, only by making some changes, provide that the clock frequency can operate the CCD, the compensating network can compensate the dynamic property of various sensors. Simulation results indicate that the dynamic performance of sensors is remarkably improved and enhanced using the proposed method.

Keywords Sensors; Dynamic compensation; Inverse systems; Compensation filter

1. Introduction

For any sensor or measuring device, we always hope that it has good response, high-accuracy, high-sensitivity, output waveform can multiple appearing input waveform without distortion, and so on. But to meet these requirements is conditional.

In the time domain, the sensor test conditions without distortion is^[1]:

$$y_u(t) = A_0 x(t - \tau_0) \quad (1)$$

In the formula, $y_u(t)$ and $x(t)$ are the output signal and input signal of sensor. A_0 is constant, τ_0 is the delay time of sensor.

When these conditions are met, the sensor output waveform and input waveform are completely similar, except that the instantaneous signal is amplified by A_0 times and delayed by τ_0 time, but the output waveform spectrum is completely similar with the input waveform spectrum, realizing transporting without distortion. However in actual dynamic test, it is difficult to find the complete undistorted sensor to meet the above conditions. The actual sensor output signal has not complete same time formula as the input signal. The difference between input signal and output signal is dynamic error.

In test, in order to reduce the dynamic error and improve dynamic response characteristic, there are two ways^[2]: one way is to change the structure and design parameters (which is often subject to many objective conditions); another way is to further process sensor output signal, that is to design a dynamic compensator. The common design methods of dynamic compensator are pole-zero collocation method, system identification method, and so on. The inadequacy of compensations is not flexible, that is only for certain types of sensors. The FIR filter compensation based on CCD device proposed in this paper has flexibility, and it can be used to compensate dynamic response of many sensors.

2. Mathematical analysis of compensation

From the functional point of view^[3], the relation between input signal $x(t)$ and output signal $y_u(t)$ of sensor $H(\bullet)$ can be expressed by mapping operator θ , the mapping relation can be written as:

$$y_u = \theta x \quad (2)$$

If the input of compensation network $C(\bullet)$ is set $y_u(t)$, and output is set $x(t)$, inverse mapping operator is set $\bar{\theta}$, there is:

$$x = \bar{\theta} y_u \quad (3)$$

System $C(\bullet)$ is called inverse system of system $H(\bullet)$, system $H(\bullet)$ is called original system correspondingly.

Shown in figure 1, the original system $H(\bullet)$ and the inverse system $C(\bullet)$ is connected in series to form composite system. It can make the input and output appear identity mapping relation, that the output signal $y(t)$ of inverse system obtains current input $x(t)$ of original system, sensor realizing reappearance without distortion of measured signal (τ'_0 in the figure is delay time of composite system).

In theory^[4], using dynamic compensation can broaden working bandwidth discretionarily. But expanding bandwidth unlimited will lead high frequency noise amplification, even submerge useful signal, resulting measurement impossible. Therefore, dynamic compensation of actual system is limited. We must consider the effect of noise or make the noise amplitude within the allowed extent.

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Based on the above analysis, we set frequency characteristics of sensor $H(a)$, its working bandwidth is a_1 . Using CCD simulating delay line constructs an inverse system $C(a)$, that is FIR dynamic compensation and the frequency characteristics $C(a)$ of dynamic compensation can be changed by adjusting clock frequency a_s of CCD device. After $H(a)$ and $C(a)$ constituting composite system in series, the frequency response characteristics is: $H(a) \cdot C(a) = K$, working bandwidth is $a_2, a_1 \odot a_2$, achieve the purpose of broadening the working bandwidth of sensor and improving the dynamic response of sensor, which is expressed by mathematic as:

$$H(a) \cdot C(a) = K, \quad 0 < a < a_2 \quad (4)$$

The frequency characteristics of the dynamic compensator can be derived by the above formula:

$$C(\omega) = \frac{K}{H(\omega)}, \quad 0 < a < a_2 \quad (5)$$

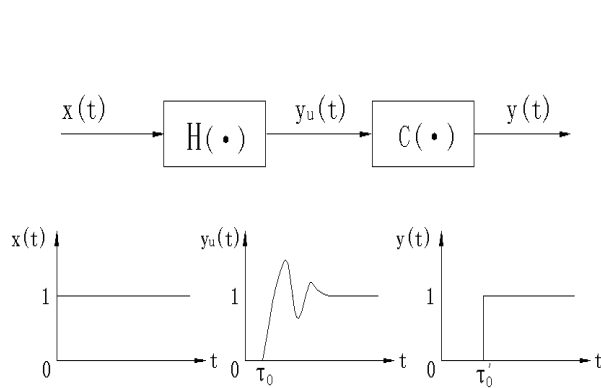


Figure 1 dynamic compensation principle

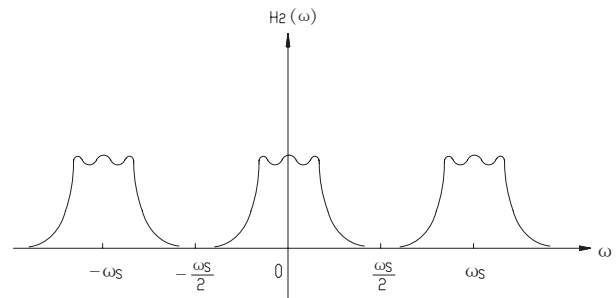


Figure2 The frequency characteristics of the dynamic compensator

3. The design of dynamic compensator

Sensor can generally be approximated as the system which is lumped, linear, time invariant[5]. The system's frequency response characteristic is complex. So the frequency response characteristic of dynamic compensator $C(a)$ is complex shown in figure 2.

$C(a)$ is expanded into index Fourier series in the interval of $[-a_s/2, a_s/2]$:

$$C(\omega) = \sum_{k=-\infty}^{\infty} h_k e^{j2\pi k \frac{\omega}{\omega_s}} \quad (6)$$

In the formula:

$$h_k = \frac{1}{\omega_s} \int_{-\frac{\omega_s}{2}}^{\frac{\omega_s}{2}} C(\omega) e^{-j2\pi k \frac{\omega}{\omega_s}} d\omega \quad (7)$$

The weight coefficient h_k of the compensator, which's frequency characteristics is $C(a)$, can be obtained from formula (7).

Infinite item summation can not be achieved in physics in formula (6). It can be obtained when taking finite items M :

$$C'_d(\omega) = \sum_{k=-M}^M h_k e^{j2\pi k \frac{\omega}{\omega_s}} \quad (8)$$

Error must exists when using $C_d'(\omega)$ approximating $C(a)$. Error size depends on cell number M , which is determined according to the request of actual test accuracy.

In formula (8), make $Z = e^{-j\omega_s}$, then:

$$C_d'(Z) = \sum_{k=-M}^M h_k Z^k \quad (9)$$

We should bring in certain delay time Z^{-M} for the formula meeting causality. Because of the unit amplitude and linear phase of Z^{-M} , so it will not change original amplitude frequency characteristics and phase frequency characteristics when multiplying Z^{-M} at both sides of formula (9). So the system function $C_d(Z)$, which is met causality, is obtained as follow:

$$C_d(Z) = Z^{-M} C_d'(Z) = \sum_{k=-M}^M h_k Z^{-(M-k)} = \sum_{k=0}^{2M} h_k Z^{-k} \quad (10)$$

The mathematical expression (10) can be achieved with FIR digital filter, which is made up of CCD device. Generally, there are two common ways: direct method and transposed method[6]. Here we use direct method. Its structure is shown in figure 3.

From formula (7), we can see that the weight factor h_k , which determines frequency characteristic of FIR compensator, is decided by sampling frequency (clock frequency) a_s . Changing a_s can change h_k , thus change the frequency characteristic $C(a)$ of the compensator. So the compensation network can compensate many sensors.

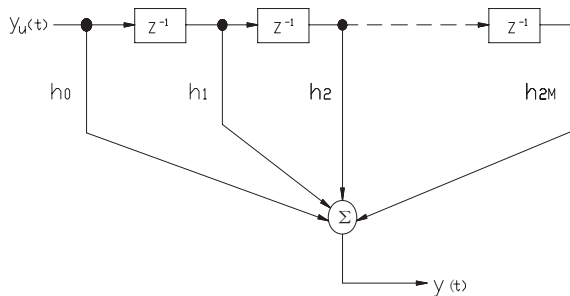


Figure 3 Use CCD consisting of FIR compensator

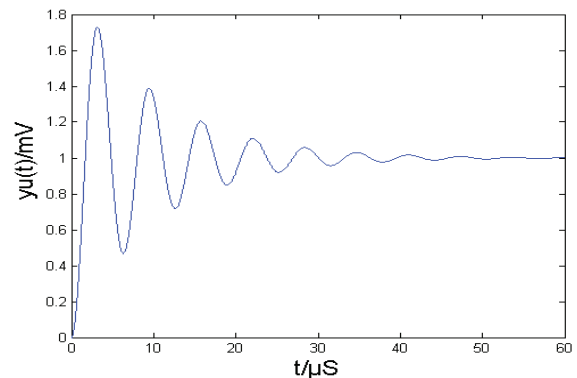


Figure 4 The step response curve of the second-order sensor

4. Calculation and simulation

We often use transient response method to study the dynamic characteristics of sensor in engineering. Because the step signal changes in an instant, so if the sensor can reproduce the step signal, then it can reproduce other input signals easily.

Piezoelectric sensor can be the equivalent of second-order sensor in certain conditions. The transfer function of second-order sensor is^[7]:

$$H(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (11)$$

The unit step response is:

$$y_u(t) = 1 - \frac{e^{-\xi\omega_n t}}{\sqrt{1-\xi^2}} \sin(\sqrt{1-\xi^2} \omega_n t + \sin^{-1} \sqrt{1-\xi^2}) \quad (12)$$

In the above formula, we use the normalized resonant frequency $\alpha_n = 1$, making damping ratio $\zeta=0.1$, $s = j\alpha$ then:

$$H(\omega) = \frac{1}{(1 - \omega^2) + j0.2\omega} \quad (13)$$

$$y_u(t) = 1 - \frac{e^{-0.1t}}{\sqrt{1-0.1^2}} \sin(\sqrt{1-0.1^2}t + \sin^{-1}\sqrt{1-0.1^2}) \quad (14)$$

The step response characteristic curve of the piezoelectric sensor is made by computer shown in figure 4.

The time domain performance index of the piezoelectric sensor can be obtained from the step response curve in figure 4:

Response maximum: $y_u(t)|_{\max} = 1.73mV$, Overshoot: $\mathcal{C} = 73\%$, Peak time: $t_p = 3.16 \mu S$

When we use FIR dynamic compensator in figure 3 to compensate the piezoelectric sensors, taking two delay units, we can obtain the output characteristic time domain equation of the sensor after compensation.

$$y(t) = h_0 y_u(t) + h_1 y_u(t - T_s) + h_2 y_u(t - 2T_s) \quad (15)$$

$T_s = \frac{1}{f_s} = \frac{2\pi}{\omega_s}$ in above formula is the unit delay time of CCD device, α_s is the sampling frequency. Weight

coefficient can be calculated from formula (7). According to Shannon sampling theorem, take the sampling frequency

$\alpha_s = 4$. When $k=0, 1, 2$, take formula (5) and formula (13) into formula (7), then we can work out weight

coefficient: $h_0 = 0.34$, $h_1 = 0.26$, $h_2 = 0.09$. So formula (15) can be written as:

$$y(t) = 0.34 y_u(t) + 0.26 y_u(t - \frac{\pi}{2}) + 0.09 y_u(t - \pi) \quad (16)$$

Take formula (14) into formula (16) and draw the step response characteristic curve of the piezoelectric sensors after compensation in figure 5.

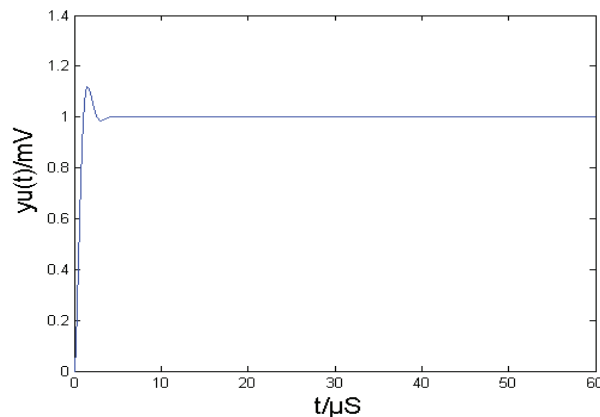


Figure 5 the step response curve after compensation

We can obtain the time domain performance index of the step response curve after compensation from the figure above:

Response maximum: $y(t)|_{\max} = 1.12mV$, Overshoot: $\zeta = 12\%$, Peak time: $t_p' = 1.38 \mu S$

From the Step response curve in figure 4、figure5 and the time domain performance index, we can see that: the dynamic performance of sensor is improved obviously, the dynamic measurement error is reduced, and the accuracy of test is improved.

Although we take a second-order piezoelectric sensors as an example and simulate it by computer, we can see from formula (5) that, the frequency characteristic $C(a)$ of compensator is only relevant to the frequency characteristic $H(a)$ of sensor, that is to say, the compensation method is also useful for higher-order sensor. At the same time, we can know from formula (7) that, the value of weighting factor h_k , which decides the frequency characteristic of compensation network, is determined by sampling frequency(clock frequency) a_s . Changing a_s can change h_k , then we can change the frequency characteristic $C(a)$ of compensation network. So this kind of compensation network can compensate dynamic characteristics of many kinds of sensors.

5. Conclusion

Dynamic compensation technology brings in new content for the research and design of sensor. We can use the compensation method in this paper to improve the dynamic characteristics of sensor well and broaden the bandwidth of sensor in the condition of not changing the structure and design parameters of sensor. It has important practical value in engineering testing field.

Because we adopt ripe MOS semiconductor integrated circuit technology [8] for CCD device in the manufacture of compensator, so this kind of compensator can be made on a small semiconductor wafer. The compensator is installed in instrument or sensor, becoming a kind of signal processing integrated circuit. It can improve the performance of instrument and sensor, and expand application scope without increasing any instrument or volume of sensor. It provides a new way for designing new kinds of sensor.

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